VOLUME 79 SEPARATE No. D-117

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

JANUARY, 1953

DISCUSSION OF THE DEVELOPMENT OF STRESSES IN SHASTA DAM

(Published in February, 1952)

By Ross M. Riegel, Roy W. Carlson, J. Laginha Serafim, A. D. Ross, J. A. Hanson, A. Warren Simonds, and J. M. Raphael

STRUCTURAL DIVISION

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N.Y.

PRICE $0.50 PER COPY

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Technical Division	*Proceedings-Separate Number*
Air Transport	108, 121, 130, 148, 163 (Discussion: D-23, D-43, D-75, D-93, D-101, D-102, D-103, D-108)
City Planning	58, 60, 62, 64, 93, 94, 99, 101, 104, 105, 115, 131, 138, 148, 151, 152, 154, 164, 167 (Discussion: D-65, D-86, D-93, D-99, D-101, D-105, D-108, D-115, D-117)
Construction	130, 132, 133, 136, 137, 145, 147, 148, 149, 150, 152, 153, 154, 155, 159, 160, 161, 162, 164, 165, 166, 167, 168 (Discussion: D-3, D-8, D-17, D-23, D-36, D-40, D-71, D-75, D-92, D-101, D-102, D-109, D-113, D-115)
Engineering Mechanics	142, 143, 144, 145, 157, 158, 160, 161, 162 (Discussion: D-24, D-33, D-34, D-49, D-54, D-61, D-96, D-100, D-122, D-125)
Highway	138, 144, 147, 148, 150, 152, 155, 163, 164, 166, 168 (Discussion: D-XXVIII, D-23, D-60, D-75, D-101, D-103, D-105, D-108, D-109, D-113, D-115, D-117)
Hydraulics	107, 110, 111, 112, 113, 116, 120, 123, 130, 134, 135, 139, 141, 143, 146, 153, 154, 159, 164 (Discussion: D-90, D-91, D-92, D-96, D-102, D-113, D-115, D-122)
Irrigation and Drainage	129, 130, 133, 134, 135, 138, 139, 140, 141, 142, 143, 146, 148, 153, 154, 156, 159, 160, 161, 162, 164 (Discussion: D-97, D-98, D-99, D-102, D-109, D-117)
Power	120, 129, 130, 133, 134, 135, 139, 141, 142, 143, 146, 148, 153, 154, 159, 160, 161, 162, 164 (Discussion: D-96, D-102, D-109, D-112, D-117)
Sanitary Engineering	55, 56, 87, 91, 96, 106, 111, 118, 130, 133, 134, 135, 139, 141, 149, 153, 166, 167 (Discussion: D-96, D-97, D-99, D-102, D-112, D-117)
Soil Mechanics and Foundations	43, 44, 48, 94, 102, 103, 106, 108, 109, 115, 130, 152, 155, 157, 166 (Discussion: D-86, D-103, D-108, D-109, D-115)
Structural	133, 136, 137, 142, 144, 145, 146, 147, 150, 155, 157, 158, 160, 161, 162, 163, 164, 165, 166, 168 (Discussion: D-51, D-53, D-54, D-59, D-61, D-66, D-72, D-77, D-100, D-101, D-103, D-109, D-125)
Surveying and Mapping	50, 52, 55, 60, 63, 65, 68, 121, 138, 151, 152 (Discussion: D-60, D-65)
Waterways	120, 123, 130, 135, 148, 154, 159, 165, 166, 167 (Discussion: D-8, D-9, D-19, D-27, D-28, D-56, D-70, D-71, D-78, D-79, D-80, D-112, D-113, D-115)

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DISCUSSION

Ross M. Riegel,[12] M. ASCE.—A major conclusion of the paper is that actual stresses in large dams are profoundly affected by the construction procedures pursued. For example, when longitudinal joints in a high dam are grouted, conditions as they exist at that time tend to be "locked up" and to remain despite the subsequent effects of the application of water load. Two illustrations may be cited. If a dam is built in two successive vertical stages, as was the case at Shasta Dam and at Fontana Dam in North Carolina, the "locking up" feature applies to the first stage. If the several blocks in a transverse section are not carried upward more or less simultaneously, stresses due to differential shrinkage and temperature effects may be similarly locked.

The process of design should consider the effects of the procedure of construction, and, if necessary, place appropriate restrictions on that procedure to the end that the behavior of the finished structure as to stresses will be that which the designers intended and expected.

A further conclusion to be drawn from the paper is that Shasta Dam is unnecessarily heavy in section. It is the writer's understanding that the heavy section was adopted to secure a high shear-friction factor at the foundation level. If so, it might be reasonably questioned whether conservatism in this respect was not on the excessive side.

Roy W. Carlson,[13] A.M. ASCE.—The analysis of stresses in Shasta Dam, as presented in this paper, is perhaps the first published account of stresses determined in a service dam from measurements of internal length changes. A remarkable fact is that the stresses so determined were confirmed in many ways: (1) All strain meters were in duplicate and good checks were shown by the duplicate meters; (2) an extra strain meter was installed in each plane and provided a satisfactory check on the dilatation at each station; (3) the average of vertical stresses as indicated by the analysis checked the known vertical loads at various ages reasonably close; (4) the moment indicated by the pattern of vertical stresses checked the known overturning moments at various ages; and (5) the directions of principal stresses varied in a consistent and reasonable manner from upstream to downstream face. Thus, it was established that the stresses shown by Mr. Raphael were reliable and accurate to a degree sufficient for engineering purposes.

Having determined the stresses at the base of Shasta Dam, it appears that economies can be achieved in gravity dams. An examination of Fig. 10 shows that very little stress developed near the downstream portion of the dam at any time. It is indicated that about 25% of the dam could have been removed from the region of the downstream face without changing the be-

Note.—This paper by J. M. Raphael was published in February, 1952, as *Proceedings-Separate No. 117*. The numbering of footnotes and illustrations in this Separate is a continuation of the consecutive numbering used in the original paper.

[12] Cons. Engr., Gibbs and Hill, Inc., New York, N. Y.

[13] Cons. Engr., Berkeley, Calif.

havior in any significant way. Gravity dams are made extravagantly thick, partly because an unreasonably large allowance is made for uplift pressure, and partly because engineers add greatly to allow for uncertainties. The Shasta analysis shows both that such a dam could be made much thinner with safety, and that there need be very little uncertainty in the degree of safety when suitable measurements are made.

The question of uplift pressure has been studied actively in recent years and the subject need not be discussed here. The writer's purpose instead is to call attention to Mr. Raphael's brilliant work in determining stresses in a service dam and to suggest the value of this accomplishment. Not only does its value to future dams promises to be great but also Mr. Raphael's service in revealing the action and safety of Shasta Dam is of immediate value. More emphasis could well be placed on providing a continuous check on the safety of important dams, now that Mr. Raphael has demonstrated how it can be done.

J. Laginha Serafim,[14] A. M. ASCE.—The information given by the author constitutes one of the most valuable contributions to the knowledge of the structural behavior of mass-concrete dams presented since the 1930's In fact the total stresses caused by all kinds of loadings, developed in Shasta Dam from the beginning of construction, were determined by a rational method.

Analysis of the data furnished by the gages embedded in concrete had not been presented before, although such instruments have been in use for more than twenty years at major American and European dams. The writer believes that this success of the analysis was aided by the fact that Carlson strain gages were used and a better knowledge of concrete was obtained.

However, in the method of stress determination used at Shasta Dam[15] there are some difficulties, namely: (1) The computations are too laborious; (2) the method requires a perfect knowledge of the volume changes caused by influences other than stress; (3) it provides little accuracy, since the theory of creep of concrete is only approximate; and (4) it requires laboratory testing of a large number of concrete specimens, cured under conditions of temperature and humidity like those of the concrete in the dam.

The coefficient of thermal expansion used for the computations was determined both from measurements made on laboratory specimens and from measurements made in the structure itself, the autogenous growth of concrete being neglected. In fact, the coefficient of thermal expansion of concrete is not constant. Moreover, if the data furnished by gages placed near the surface are considered in determining its magnitude, the results will not be very reliable, especially if the gages are placed near the downstream face of the dam, where both capillarity[16] and shrinkage phenomena occur. The use of concrete prisms (located in the interior of the dam) for the purpose of control measurements involves the risk of humidity changes in the chamber separating the prisms

[14] Head, Dams Studies Section, Lab. of Civ. Eng., Structural Branch, Lisbon, Portugal.

[15] "Determination of Stresses from Measurements in Concrete Dams," by J. M. Raphael, Third Congress on Large Dams, R-54, Stockholm, Sweden, 1948.

[16] "Beanspruchung von Gewichtstaumauern durch das strömende Sickerwasser," by K. Terzaghi, *Die Bautechnik*, Vol. 12, 1934, p. 379.

from the dam concrete, in which case the prisms might be subject to conditions different from those of the mass concrete. This fact has been recognized in making similar measurements at Portuguese dams. The Laboratório de Engenharia Civil, Ministério das Obras Publicas, in Lisbon, Portugal, uses the arrangement illustrated by Fig. 13, which has the following advantages: The concrete that encloses the gages is (1) integral with the mass concrete; (2) free to undergo changes in length; and (3) protected against the air in the chamber by copper foil. Such an arrangement eliminates the difficulties in the determination of volume changes.

The influence of creep remains the most difficult problem to be solved in determining the stresses from strain measurements in mass concrete. Creep of concrete, as well as any other mechanical properties of concrete, cannot be determined without a dispersion of the results, even when the determinations are made at the same time on prisms of the same concrete cast on the same date. Creep is not entirely proportional to stress, not even for low stresses,

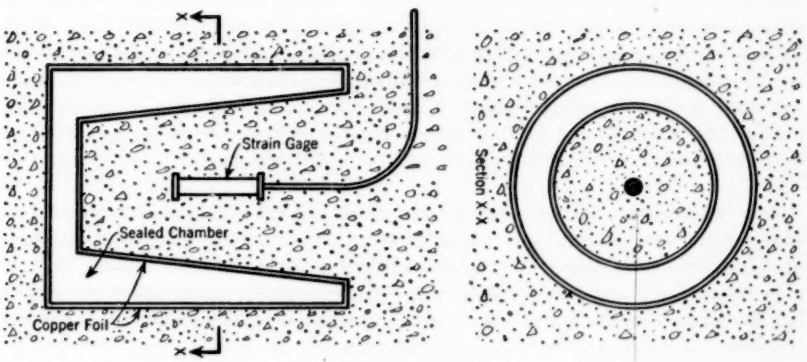

FIG. 13.—NULL-STRESS METER

and it is probably affected by the three-dimensional state of stress. In addition, it is affected by temperature and humidity conditions; the slow penetration of the water into the pores of concrete in hydraulic structures is a process that depends on many variables.

All these facts must be taken into account in laboratory testing. This requires a large number of different tests.

The author found that the stresses in the center of the dam are higher than those near the faces. This suggests the following explanation:

In a number of tests in tunnels, it has been found that the deformability of large rock masses is always greater than that of concrete, even after grouting (which no doubt decreases deformability). In like manner, the foundation rock of Shasta Dam may be more deformable than the concrete; this would account for the unusual stress distribution.

The differences between reaction and external loadings, illustrated in Fig. 9, were ascribed to the partial support of Row 43 exerted by Row 42 and Row

44. However, it is also possible that such differences are ascribable to the deficiencies inherent in the method, in which case information would be available concerning the accuracy it provides. A full explanation of the accuracy of the method would greatly increase the value of the author's paper. In fact, though in a gravity dam like Shasta, it is possible for the final check of stresses to be made statically by comparing the reaction with the external loads, the writer does not know how such a check could be made in the case of an arch dam.

The writer questions conclusions with regard to the possible savings in gravity dams. Before it becomes possible to consider saving concrete in gravity dams having the usual cross sections, a full and detailed explanation of the determined stresses (including temperature stresses) will be required. For instance, models might be tested in which the foundation rock could be faithfully reproduced. In a gravity dam, the factor of safety against overturning is much lower than the usual safety factors encountered in structural engineering. On the other hand, the author fails to state whether the pore pressure in the concrete, and the uplift in the foundations, have reached their maximum values, corresponding to the steady state.

Because of its value, this study by Mr. Raphael deserves to be completed, with any available measurements of deflections, joint opening, temperature, pore pressure, and other factors influencing the stresses, so as to give a more complete picture of the structural behavior of the dam.

A. D. Ross[17].—Admiration and the closest study are due this paper because it is the result of a determined attempt to obtain the actual stresses in a major structure. Analytical studies and tests of materials and models can give much useful information; but knowledge of the behavior of the actual structure is the ultimate objective and it is both stimulating and encouraging to have these satisfactory records covering a long period.

The postulation of the creep surface is a reasonable approach to the problem and it is clearly of the correct general form for the three variables to which it relates. Thus, if—by careful control—the analyst eliminates the differences in creep caused by the water-cement ratio, the class of cement, the mineral character and grading of the aggregate, the ambient humidity, and other significant factors, a sufficient number of tests under constant sustained stress will define the creep surface for a particular concrete, but will not solve the problem of varying stress. This leads to a consideration of the effective modulus in Eq. 4. For the condition of constant stress, this equation is obviously correct and it is probably adequate for practical purposes when the stress is varying slightly and gradually—as, for example in the relaxation of prestressed concrete. It is less satisfactory, however, when the stress varies markedly and rapidly, and particularly when there is a reversal of stress. The equation is based on the assumption that the stress, σ_x, at any time, t, is uniquely determined by the effective modulus E', and the total strain ϵ'_x. However, it is possible to have two identical concretes exhibiting, at the same instant, the same total strain while carrying quite different stresses. This will happen if the stress histories

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prior to that instant have been different. In other words (taking an extreme example), assume that two identical specimens have been maintained under a tensile stress of 100 lb per sq in. and a compressing stress of 1,000 lb per sq in. After (say) 3 months, the stress in the first is also raised to 1,000 lb per sq in. in compression. The total strains in the two specimens will never be the same although Eq. 4 suggests that at all times after 3 months the strains would be identical.

The writer appreciates that the semi-graphical construction in Fig. 4 is designed to deal with this difficulty, but does it really take into account the previous stress history? For example, between (say) 30 days and 40 days in Fig. 4 it would be incorrect to estimate increments of elastic strains plus creep strains from the creep surface for $K = 30$ days and $t = 0$ days to $t = 10$ days because these are appropriate only to concrete, that is, 30 days old and previously unloaded. To explain it less scientifically, much of the potential creep can be "squeezed out" of concrete if it is stressed early in its existence. The writer has made a mathematical analysis[18] that takes into account a variable stress history; but the problem is intrinsically a difficult one and the writer cannot claim that it is more than an approximation (and then only for unidirectional stress) because the equations neglect the effects of aging. Doubtless the construction of Fig. 4 resulted from the assumptions that the principle of superposition was applicable to the problem and that creep was wholly recoverable. Although these assumptions might apply to a very mature concrete, it seems unlikely that they can be true early in its existence.

Additional questions with regard to the computation of stresses also arose. Were the laboratory tests for the basic creep data conducted under uniaxial or triaxial conditions; and were the ambient conditions normal atmospheric or were they comparable with those of the interior of the dam? These questions seem important because creep appears to be due primarily to colloidal seepage and it is well known that the ambient humidity is a most influential factor in the question of creep. Incidentally, this condition would lead to the expectation of a greater creep—and therefore a reduction in stress—near the exposed downstream face of the dam. Also, it would be interesting to learn how the Poisson effect was handled in the computations. For short-period loading, concrete behaves very much like an elastic material with a relatively low value of the Poisson ratio, but was the Poisson effect considered in any way when computing creep strains? The writer's studies of concrete under various states of plane combined stresses suggest that the creep in the direction of one principal stress is quite independent of the creep along the orthogonal axis; that is, the Poisson ratio for creep strain seems to be zero. Finally, it is of interest to inquire whether any difficulties with zero drift of the strain gages were encountered—in view of the long period of service.

The effects that some of these uncertainties would have on the computed stresses are problematical, although they might help to explain the discrepancies between load and reaction that are noticeable at the end of 1943 in Fig. 9. In view of the complexity of the problem, close agreement between load and

[18] "Creep and Shrinkage in Plain, Reinforced and Prestressed Concrete," by A. D. Ross, *Journal*, Inst. of C. E., Vol. 21, No. 1, 1943, p. 38.

reaction throughout 4 years could scarcely be expected and the author is to be congratulated on this paper, which, by the frank presentation of data derived from a variety of methods, must give much reassurance to designers.

J. A. HANSON[19].—The factual information on actual stresses developed in a structure, as reported by Mr. Raphael, should be studied by all designers of large concrete dams. In the limited space available, the author could not present the background of the creep theory as used by the USBR. This discussion describes in brief the laboratory studies, made by the writer and others, that substantiate the author's method for analyzing the effect of creep on stresses in Shasta Dam.

The problem of creep in structural behavior investigations of mass concrete involves approximations. In the writer's opinion, these approximations are no larger and of no more importance than similar assumptions made in the theory of elasticity as applied to concrete. At best, concrete is only a "statistically" homogeneous and isotropic material and, as Mr. McHenry states,[7] "It is almost axiomatic that when dealing with concrete any thought of high precision must be dropped at the outset." Such a situation does not preclude the application of either creep or elastic theory to concrete, but indicates a practical limit to profitable refinements of structural analysis.

The theory of creep in concrete as used by the USBR is represented by Eq. 5 and Fig. 4, and is simply a theory of "delayed" elasticity. As such, it requires superpostition of time effects and direct proportionality of creep to stress within the working range. Two of the creep-testing programs in the Engineering Laboratories (USBR) were designed to check these specific items for mass concrete. Superposition of time effects is easily and rigidly checked by comparison of measured and computed creep recovery. This computation, of course, must take the aging characteristics of concrete into account. In one of the programs, the computed recovery was from 100% to 120% of that measured and, in the other program, greater than 80%. Proportionality of creep to stress has been shown indirectly by the recovery measurements and was also demonstrated directly by loading similar test specimens in pairs so that the stress intensity of one was twice that of the other. These pairs of loadings were applied to specimens of four different ages, up to 90 days. In each case, the magnitude of creep from the higher load was twice that from the lower load within the normal dispersion of the data.

The interior of a large mass of concrete must retain the original moisture content, and this condition is duplicated in the laboratory by sealing the specimens in waterproof jackets. Several tests have shown that sufficient precision for determining stress from measured strain may be maintained even though the temperature effect on creep is neglected. In these tests, the sealed concrete was subjected to loads that maintained constant length or a particular strain history while undergoing a typical mass-concrete temperature cycle. Two such tests were reported by Mr. McHenry.[7] Stresses were com-

[19] Structural Research Engr., Eng. Laboratories, Bureau of Reclamation, U.S. Dept. of the Interior, Denver, Colo.

[7] "A New Aspect of Creep in Concrete and Its Application to Design," by Douglas McHenry, *Proceedings*, A.S.T.M., Vol. 43, 1943, p. 1069.

puted from the strain data by the step procedure described by the author, using constant-temperature creep functions. The agreement between measured and computed stress was good in all cases, indicating that, although temperature effect on creep may be of interest from a research viewpoint, it is not of great importance in structural behavior studies of large dams.

The aging characteristic of the particular concrete is the most important single factor affecting creep and instantaneous strain. It is not necessary that a large number of specimens be tested when determining the effect of age on the creep function for a particular structure. The routine program at the Engineering Laboratories consists of a total of only ten specimens of 6-in. diameters. Duplicate specimens are loaded to constant stress at ages of 2 days, 28 days, and 365 days. Single specimens are loaded at ages of 7 days and 90 days and two specimens function as free controls. As a check on the extrapolated creep function, the 7-day and 90-day specimens are unloaded at 1 year, allowed to recover to age 5 years, and then reloaded.

Measurements of recovery and creep from different load intensities have validated the principles of superposition and stress proportionality in the creep theory. The laboratory comparison of the computed and measured stresses and the separate check of equilibrium between the stress distribution and the applied loads in the structure have demonstrated that reliable values of existing stresses can be determined even though minor influences on the creep of concrete are neglected.

A. Warren Simonds,[20] M. ASCE.—The distribution of stress within a massive concrete dam has been a problem of concern to designers for many years. It has long been recognized that, in analyzing a dam section, the assumption of linear variation of stress distribution was not correct. Consequently, numerous attempts have been made to evaluate existing conditions more closely, following three general methods: (1) Mathematical analysis, (2) model analogies, and (3) analyses based on observations made with instruments embedded within the mass of the structure. Mr. Raphael has made use of method (3) in his evaluation of stresses in Shasta Dam. This investigation, made with an improved type of strain gage, has resulted in a thorough and complete evaluation of the stresses that substantiates the theory of nonlinear stress distribution along the base of the dam.

From a study of the stress diagrams, it is apparent that the method of construction has a profound effect on the distribution of stress along the base of the structure. The fact that block construction was used at Shasta Dam and that the joints between the blocks were not grouted until after a considerable height of concrete above the foundation had been placed and cooled, undoubtedly contributed to the shape of the stress curves shown in the paper. If Shasta Dam had been built using long monolithic blocks extending from the upstream to the downstream face (a practice now discontinued in building very large dams), and if the concrete had been cooled to different temperature conditions, the resulting pattern of stress distribution would have been

[20] Engr., Bureau of Reclamation, U.S. Dept. of the Interior, Denver, Colo.

changed materially. In such a case, stresses much higher than those given by the author might have developed under similar loading conditions.

The strain measurements show that the effects of temperature variation on the concrete in the area near the surface range through a fairly large cycle (see Fig. 5(*b*)). Although the annual change in the interior of the mass concrete may be small, the daily variation at the surface may account for the extensive patterns of shallow cracks that are frequently observed on exposed areas. Annual variations in the stress cycle of the order of 800 lb per sq in. to 1,200 lb per sq in. are sufficient to cause cracks to develop.

Information that should be of interest to designers is the diagram showing the results of the author's computations of three-dimensional principal stresses from the stresses measured along the individual axes of the strain-meter groups (see Fig. 8). The appearance of tension among the second principal stresses is noted particularly in the vicinity of a rock pinnacle in the foundation. This tension may be the cause of cracks in the concrete which are observed frequently near irregularities in the foundation or abutments.

It is of considerable interest to note, in Fig. 7, the development of stress as the dam was built and as the reservoir filled. A condition little realized by most designers is emphasized—namely, that the construction procedure and temperature changes have greater influence on stresses in gravity dams than does the water load.

Most gravity dams are designed with a reasonable factor of safety based on a maximum condition of loading. Frequently, the assumed maximum loading is obtained by combining a series of loads or conditions that are likely to subject the structure to the highest allowable stress. Although it is assumed that the structure may be subjected to the most severe load conditions at one particular time, it is possible (but not probable) that this condition actually will occur. The stresses shown on the diagrams presented by the author are the results of observations made when the dam was subjected to only a fraction of the load assumed for design purposes. It will be interesting to observe the stresses that develop in Shasta Dam when it is subjected to a more severe condition of loading—one that presumably resembles more nearly the loading condition assumed in the design.

J. M. RAPHAEL,[21] A. M. ASCE.—The interest shown in this paper, evidenced by the commendatory remarks, by the questions raised by the criticisms made, and by the supplemental data presented, is gratifying to the author.

Mr. Riegel has assumed correctly that the heavy cross section of Shasta Dam was dictated by stability requirements, using conservative assumptions for the shear-friction factors.[22] In answer to Mr. Riegel's question as to whether conservatism in this respect was not on the excessive side, the USBR design criteria have been reviewed and restated as a result of studies made on actual dams. Present designs now being planned for construction reflect the new criteria and design concepts in their generally leaner outlines.

[21] Head, Structural Behavior Group, Bureau of Reclamation, U. S. Dept. of the Interior, Denver, Colo.

[22] "The Design of Shasta Dam," by Kenneth B. Keener, *Civil Engineering*, July, 1943, p. 317.

Mr. Carlson also discusses the economy of the structure, pointing out that, from the standpoint of stress distribution, approximately 25% of the dam could have been removed from the region of the downstream face without changing the behavior significantly. In this connection, Mr. Simonds' remarks serve as a timely reminder that the dam has never experienced the maximum stresses for which it was designed. Maximum high water was not reached until May, 1952. Prior to the present writing (1952), no earthquake has occurred near the structure that would cause the accelerations for which it was designed. Similarly, uplift pressures have been only a fraction of the design pressure, attesting to the efficiency of the grout barrier and the drainage system. However, in a gravity dam, it is not usually the stress distribution or the magnitude of stress but rather the stability factor that controls the design.

Mr. Serafim comments that, in the method of stress determination used at Shasta Dam, the computations are too laborious. This is all too true of the method in use at the time of the Shasta Dam analysis. However, since that time several improvements have been made in the computation methods of the USBR. The most important of these improvements was the successful use of punched-card machines to do the actual work. By using the machines and a

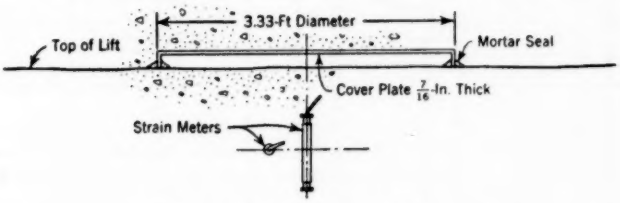

FIG. 14.—UNSTRESSED STRAIN METER DETAIL

more streamlined computation method, the analytical process has been accelerated sufficiently so that stresses now can be determined shortly after the field data are obtained. As an example, the USBR has been able to follow the actual development of stress in the base of Hungry Horse Dam, in Montana, as concrete was placed and the reservoir rose. Results from this and other major USBR dams should be available for study after 1953.

When Mr. Serafim states that the coefficient of expansion of concrete is not constant, he is perhaps placing too much emphasis on early-age behavior. The USBR has found some evidence indicating an early high value of the coefficient of expansion, which drops rapidly to a constant normal value within the first day. However, this condition is a phenomenon of the chemical expansion of the cement in the concrete during the first heating cycle, and is not applicable thereafter. The coefficient of expansion varies slightly with age. To put it in its proper perspective, the coefficient of expansion of various types of concrete ranges through a few millionths of an inch per inch per degree Fahrenheit, from 4×10^{-6} in. per in. per degree Fahrenheit to 7×10^{-6} in. per in. per degree Fahrenheit. Observed variation of any concrete with temperature varies by about one ten-millionth of an inch per inch and the variation with age is still less. The magnitude of stress error introduced by ignoring the variation with tem-

perature for a concrete in which the temperature range is about 30°F is less than 10 lb per sq in.—with correspondingly less error introduced by ignoring the effect of age. In any case, considering the length of the record involved in dam measurements and the general low values of stress the first day, the USBR has neglected this effect in its analysis.

Mr. Serafim's suggestion to make control measurements for the coefficient of expansion and the growth at points remote from the surface is good, as is the scheme he uses to embed the strain gage in mass concrete. Similar considerations led the USBR to the installation shown in Fig. 14, which was used at two recent dams. In these dams the vertical meter near the top of the lift measures, in effect, the coefficient of expansion—with possibly some contri-

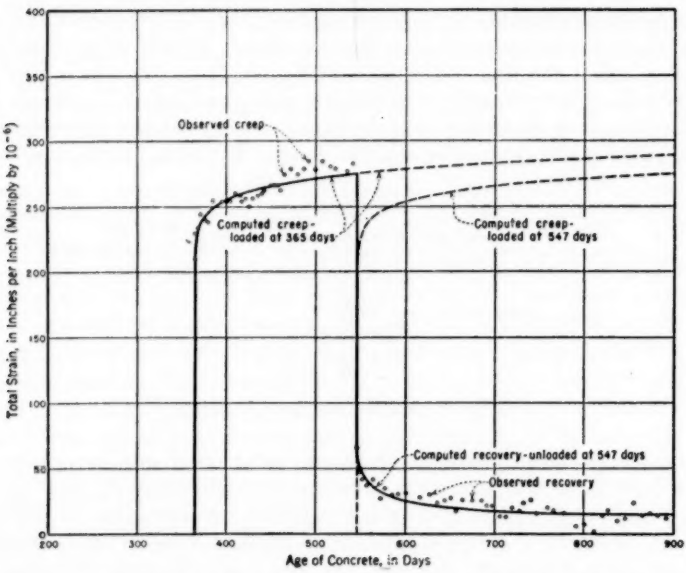

FIG. 15.—RECOVERY PREDICTED FROM CREEP CURVES, USING THE PRINCIPLE OF SUPERPOSITION

bution, through Poisson's ratio, of a fraction of the horizontal strain. The latter is evaluated separately by the horizontal strain meter. In this respect, Mr. Serafim's installation is superior; there can be no side effects if the copper container is flexible enough.

Mr. Serafim's remark that the deformability of large rock masses is always greater than that of concrete is thought-provoking, to say the least. In attempting to gage the effect of foundation rigidity on the stresses in Shasta Dam, the author used the results of bearing tests made directly on the foundation rock. These tests indicated that the modulus of elasticity of the foundation rock was four to five times that of the concrete of the dam. It is understood that Mr. Serafim's tests utilize bearing areas almost ten times as large as those used at Shasta Dam and may reveal facts not shown in USBR tests.

Also, in Mr. Serafim's tests, the actual bearing is accomplished by a steel capsule rather than by the mortar patch and rigid plate used by the USBR. It is hoped that the results of this work by the Laboratório de Engenharia Civil will be published soon.

Most of Mr. Ross' objections to the method of computing stress from a varying strain history hinge on the validity of the principle of superposition. Perhaps the results of an experiment made to test this principle will answer his objections. Fig. 15 shows the observations of a sealed cylinder of Shasta Dam concrete loaded at 1 yr with a constant load of 500 lb per sq in., and unloaded at $1\frac{1}{2}$ yr. The circled points are actual observations. The smooth lines are taken from the creep surface. The part of the curve representing recovery is plotted as the difference between the curves of 1-yr loading and $1\frac{1}{2}$-yr loading. It can be seen that the observed data follow very closely the theoretical lines derived using the commonly accepted understanding of the applicability of superposition. For a similar experiment using results at any earlier age when the concrete is more deformable, the reader is referred to Mr. McHenry's classic paper on the subject.[7]

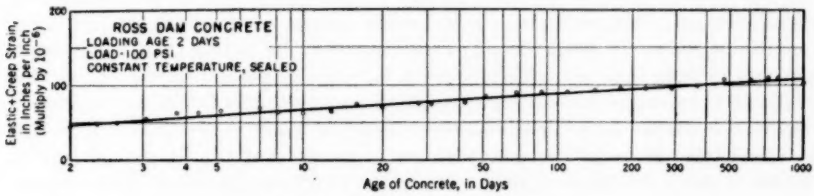

FIG. 16.—SPECIMEN CREEP RECORD

The author has seen no evidence to support Mr. Ross' theory that "potential creep can be 'squeezed out' of concrete if it is stressed early in its existence." On the contrary, the normal behavior is as shown on the creep surface, in Fig. 3, which is plotted from experimentally observed data. Perhaps this fact might be shown more emphatically by plotting the observed results for 2-day loading at 100 lb per sq in. for the concrete at Ross Dam, in Washington, on semilog paper, as shown in Fig. 16. This curve represents the expression:

$$\epsilon = 100[0.480 + 0.0898 \log_e(t+1)]$$

Fig. 16 shows that, at the end of 1,000 days, there was no evidence that creep had been squeezed out of the concrete.

In one series of tests, run especially to find the effect of creep on the Poisson ratio, it was found that the range of values for the Poisson ratio for concrete loaded at a particular age was very narrow—for example, between 0.15 and 0.17. At the same time, it was found that the range of the variation of the Poisson ratio with age at first loading was much larger, of the order of between 0.12 and 0.19. This variation was used in the analysis of strain meter data for the dam. It was not found that the Poisson ratio for any age of loading was zero, as suggested by Mr. Ross. However, these were all uniaxial tests; no tests of creep under triaxial conditions have been made by the USBR.

Indeed, the author is not aware of any published results of triaxial creep tests. This field might be fruitful for further study.

Mr. Hanson elaborates on tests and controls used by him to establish the creep properties of Shasta Dam concrete. It is considered that the number of specimens used to establish the creep properties of a particular concrete is quite modest as compared, for instance, to the number of cylinders used to control the strength of concrete being used in a dam. As the creep properties of concrete gain in importance to designers of concrete structures, tests of creep will become more common, and more information will become available. Mr. Hanson's array of tests might well form the nucleus of a standard test for creep in concrete.

Mr. Simonds, one of the pioneers of model dam testing, shows the place of this prototype investigation among the three general methods for investigating the distribution of stress within a massive concrete dam. Each method has its limitations. Mathematical studies usually are limited by the necessity of expressing body and boundary forces in some mathematical form which may only approximate actual conditions. Load applications and boundary conditions usually must be modified greatly in models for ease in fabrication and manipulation. Mr. Serafim has indicated a step in the right direction by modifying his model foundations to correspond to the actual state. Although prototype tests indicate faithfully what happens in the actual structure, it is difficult to separate the several causes in the over-all effect. When more data become available, multiple correlation should be used.

Probably the most important design principle that can be gained from a study of the distribution of stress at the base of Shasta Dam is that the dimensions of a structure constructed like Shasta Dam cannot be increased indefinitely without some parts of the dam going out of action. However, the results cited are only for Shasta Dam; they do not really constitute sufficient data from which to draw general conclusions applicable to all concrete gravity dams. Only when many dams have been studied in this manner can the special conditions applicable to the individual dams be separated from the general laws that apply to all concrete dams. It is hoped that by the stimulus of this example the many investigations known to be underway in the Americas and Europe can be brought to successful and fruitful conclusions, and that the results can be made available for correlative studies. From inquiries received from dam designers in England, France, Portugal, India, and Australia, as well as from other agencies in the United States, it is believed that this paper is but the forerunner of many more after investigations now (1952) contemplated are completed. If this wealth of material becomes available, the paper will have served its purpose.

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